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ABSTRACT

Digitally enhanced Landsat MSS data have been used to discriminate among basalt flows of historical to Tertiary age, at a test site in Northwestern Saudi Arabia. Spectral signatures compared favorably with a field-defined classification system that permits discrimination among five groups of basalt flows on the basis of geomorphic criteria. Characteristics that contributed to age definition include: surface texture, weathering, color, drainage evolution and khabrah development.

The inherent gradation in the evolution of geomorphic parameters, however, makes visual extrapolation between areas subjective. Therefore, incorporation of spectrally-derived volcanic units into the mapping process should produce more quantitatively consistent age groupings.

INTRODUCTION

Over the past two decades satellite-derived imagery has gained increasing acceptance as a tool for regional geologic mapping. The success of geological interpretations of photographs obtained during sub-orbital and the early manned Mercury flights led to NASA implementation of the Synoptic Terrain Photography Experiment developed by P.D. Lowman. This experiment, carried on all manned Gemini flights (1963-1966), required astronauts to photograph predetermined areas of the earth's surface that were selected on the basis of their geologic significance (Lowman 1980). It was not until late 1972, however, that global, high resolution, multispectral data became available with the launch of ERTS (Landsat)-1.

The initial extraction of geologic information from Landsat data continued to rely heavily upon photo interpretation of imagery. As more specialized requirements evolved, however, increasing emphasis was placed upon the development of digital enhancement procedures and information techniques to exploit the full information content inherent in the digital multispectral data.

Ratio and contrast enhancement algorithms developed at the Jet Propulsion Laboratory (JPL) in collaboration with the U.S. Geological Survey permitted discrimination of rock types in the semiarid areas of South-central Nevada (Rowan et al 1974). These algorithms were modified by Moik (1980, p. 158) and applied to mapping several large areas within the Arabian Peninsula (Blodget et al 1978 and Blodget and Brown 1982). Our current research is designed to determine if similarly enhanced Landsat imagery can be successfully applied to discriminate among volcanic eruptives of different age, based upon surface texture and composition in the arid environs of Western Saudi Arabia (Figure 1).

The initial enhanced imagery used in this study was created by the Environmental Research Institute of Michigan for the U.S. Geological Survey, Office of International Geology. Subsequent processing was accomplished using the interactive ESL/IDIMS system at the NASA Goddard Space Flight Center.

PREVIOUS WORK

The earliest mapping of the volcanic flows of our test area, using orbital imagery, was published by Bannert (1969). This small scale geologic map was interpreted from a Gemini-4 photograph (S-65-34665) at a scale of approximately 1:1,100,000; it divided the eruptives into four categories based primarily upon color differences, texture and superposition. Results compared favorably with the most recent published geologic map of the area (Brown et al 1963).

The potential contribution of digitally processed Landsat data for discriminating among volcanic flows in northwestern Saudi Arabia was recognized by Blodget et al (1975). Independent digital Landsat mapping in the Craters of the Moon Volcanic Field, Idaho (Lefebvre 1976) determined that spectral differences between volcanic flows could be attributed to various factors including surface roughness, surface chemistry and surface cover (weathering, sediments and vegetation).

Earliest field mapping of the volcanics in the study area was accomplished at the reconnaissance level by Brown and published at 1:500,000 scale (Brown et al 1963). More definitive mapping of the Harrat Khaybar volcanic chain immediately to the north of our test area was completed a decade later by Baker et al (1973). Subsequent mapping of the area on 1:100,000 quadrangles by the staff of the Bureau de Recherches Geologiques et Minieres Saudi Arabian Mission was completed during the mid-1970's and synthesized into the two 1:250,000 published quadrangles by Delfour and Dhellemmes (1980) and Pellaton (1981).

GEOLOGY

Regional

Our test site includes the Cenozoic volcanics within Landsat screen 1446-07195 (path 170, row 43). These extrusives overlie Precambrian basement that now forms the eastern portion of the Arabo/Nubian shield.

Vulcanism beginning in mid-Tertiary and continuing up to Holocene covers vast plateaus in Saudi Arabia, Yeman and Ethiopia. In Saudi Arabia 13 separate volcanic areas, extending along the Red Sea coast and the adjacent scarp mountains, cover about 90,000 km^2. Two major periods of vulcanism, the earlier from mid-Oligocene to mid-Miocene, consists of flows ranging from picrite-ankaramite to alkali-olivine basalt (Coleman et al 1983). A hiatus of about 10 ma followed during which a thick series of evaporites were deposited in the Red Sea rift. The second epoch of vulcanism began with earliest Pliocene and continued to the Holocene. These younger flows range from hawaiites and alkali-olivine basalt to trachyte, phonolite and rhyolite ejecta, becoming bimodel during the Pleistocene and Recent. They were accompanied by the ramping of the Western Arabian Highlands. The Arabian plate rotated counterclockwise during this epoch as the Red Sea rift widened and an inner rift valley grew.

Test Site

Geologically the test site can be divided into three distinct units. The southwest corner is made up of sediments and terraces that form the Red Sea coastal Plain. The remaining area is part of the Precambrian Massif consisting of complexly folded, metamorphosed, granitized rocks that are locally intruded by granitic and rarely gabbroic rocks of Upper Proterozoic age. In much of the northeastern two-thirds of the scene, the basement is covered by extensive Tertiary and Quaternary extrusives consisting primarily of olivine basalt flows which have localized trachyte and phonolite cones along their axis. Remnant Cambro-Ordovician sandstones are present in rare outcrops in the northeast corner where they cap small buttes that have resisted erosion. Quaternary surficial deposits fill closed topographic depressions and wadi floors.

Volcanics

Tertiary and Quaternary basalts in the test area include parts of three of the great basalt plateaus (harrats) that cover much of the western Arabian Shield (Figure 2). These are Harrat Rahat that extends northward from the southeast corner of our scene, Harrat Khaybar that covers much of the northern margin of the image and the Harrat Hirmah that is located between the two. Erosional remnants of older flows perched on top of prominent buttes near the center of the test area mark the southern terminus of the Harrat Khaybar.

Harrat Rahat consists of a north-northwest-trending series of flows that lie asymetrically about a chain of volcanic craters and cones. These vents are commonly preserved as breached craters and domes of lava and pyroclastic material. The youngest are intact and dominate the topography; the oldest have been eroded and flattened. Thickness of the basalt along this spine averages 200-300 meters, but in some locations it has been determined by drilling to exceed 400 meters (Pellaton 1981).

Harrat Khaybar, the largest of the great flood basalts on

the Arabian Peninsula, terminates in the northern part of our test site. Most lavas flowed both to the east and to the west from the Jebel Abyad volcano chain in the center of the plateau. Near the southern terminus, however, these vents have generally been strongly degraded by erosion. Individual flows can be mapped and dated on the basis of their tone, texture and morphology on aerial photographs. While mapping the flood basalts, Delfour and Dhellemmes (1980) developed a classification scheme for mapping and dating these regional flows, a scheme extended southward into our test area with minor modifications by Pellaton (1980).

Harrat Hirmah, situated between Harrats Khybar and Rahat, has been extensively modified by erosion; the boundaries between flows in such dissected terrain can be difficult to map.

Age Classification of Volcanics

Volcanic structures in the area have been variously altered by erosion and depositional processes. The oldest remain as flattened cones and flow structures while the youngest surfaces are nearly intact. Combining field study and interpretation of aerial photography, Delfour and Dhellemmes (1980) were able to develop a 5-stage geomorphology-based classification that could be applied throughout the area. Subsequent potasium/argon dating of selected samples provided age determinations for the individual units. Their classification can be summarized as follows:

Unit	Description
b5	Basalt flows are generally 7-8 meters thick and stand out in relief. Their surfaces can be either smooth, ropy (pahoehoe type) or scoriated and brecciated (aa type), and they display flow structures. No trace of erosion is visible. Clay and silt deposits filling depressions are marked by swarms of very small patches. Flows range in age from Historic (1250 AD) to 30,000 years (geologically Recent). On aerial photography, flows are black or very dark grey. They are composed of alkaline basalts which are not distinguishable in mineralogy or chemical composition from classes b4, b3 or b2. They are however clearly different from b1 which is basinite (feldspathoidal basalt).
b4	Basalt flows issued from scoria cones stand out in relief with morphology well preserved. Surfaces are slightly smooth and drainage patterns are developing. Sand and clay deposits fill small depressions. These flows range in age from 30,000 to 300,000 years (late Quaternary), and appear dark grey on aerial photographs.
b3	Flow edges are clearly defined even though they have been considerably affected by erosion. A clear but shallow drainage pattern is visible at the surface. Clay and sand filled depressions are common and

widespread, and locally adequately large to form sandy silt flats (khabrah). The flow surface forms a reg with deposits of gravel between well rounded basalt blocks. Weathering is several cm. deep and surfaces are frequently covered by desert varnish (patina). The age of these flows ranges from 300,000 to 3,000,000 (3 ma) (Pleistocene and upper Pliocene). They are dark grey on aerial photographs.

b2 Flows are extensive but emission centers are mostly covered by more recent flows. Individual flows are less well-defined than those of the later basalts but still stand out in relief. The edges, however, have sometimes been eroded smooth. The drainage pattern is much more clearly defined, widespread and mature than b3, and erosion has commonly cut even deeper than the thickness of the flow itself. Khabrah deposits are more numerous and widespread than in b3. It should be noted that while the limit between b3 and b2 is fairly clear at the extremity of some flows, it is much less clear further up the flow. These basalts are generally distinguishable on aerial photographs by a paler color than other basalts. Age of the b2 unit ranges from 3 to 6 ma. (Lower and Middle Pliocene).*

bl Flows of basinite composition are found along the western margin of the Harrat Khaybar and frequently occur as isolated units capping buttes. Few remains of volcanic structure are preserved and it is not possible to distinguish any break in slope between successive flows. Drainage is very dense and very clearly defined with large wide or deeply incised wadis. Most of the khabrah deposits have disappeared due to surface erosion or basin capture. The surface of these flows appears as a reg with sand and gravel deposits between the very rounded lava blocks that have a black patina coating. On aerial photography these units are pale grey in color. Age of the basinite flows ranges from 6 ma to 9.1 ma (Lower Pliocene).*

*Pellaton (1981) dates b2 as 3-9 ma and bl as 9-25 ma (Lower Pliocene and Miocene).

A group of trachyphonolite domes are locally present along the center of Harrat Rahat and form its highest peaks; some elevations exceed 1,300 meters. Eruptions from these vents were accompanied by abundant pyroclastic activity which formed thick layers that have since been severely eroded. These rocks range in age from .2 to 5 ma (Pleistocene to Middle Pliocene) (Pellaton, 1981).

METHOD

Basalt fields of different ages have previously been found to exhibit strikingly different colors on imagery constructed from contrast-enhanced, ratioed Landsat data (Blodget et al 1975 and Blodget and Brown 1982). Here more detailed mapping by the French geologists in the Medina area

furnishes a check on spectral units defined on such enhanced Landsat imagery.

Figure 3 is a color composite image constructed using ratio data from Landsat scene 1446-07195. Ratio values for multispectral scanner (MSS) bands 5/4, 6/5 and 7/6 were projected through blue, green and red filters respectively; each ratio data set had been contrast-enhanced prior to compositing.

This digitally enhanced Landsat image was carefully compared with the 1:250,000 geologic map of the al Madinah Quadrangle (Pellaton 1981) to determine how well the six clearly mapped eruptive units would correlate with distinctive spectral units.

RESULTS

A preliminary scan of the enhanced image immediately shows that nearly all volcanics mapped in the test area correlate with spectral units of a distinct set of hues. The limits of specific units, however, are locally not in agreement. Thus, a point-by-point comparison was made to assess the merits and limitations of spectral mapping.

The trachyphonolite mapped along the spine of the Harrat Rahat is nearly identical to tan/tan-yellow signatures on the image. Individual cones within these areas are clearly discernible on both enhanced and standard Landsat imagery.

The black signature at the northern end of the Harrat Rahat clearly correlates with several b5 flows defined on the geologic map. In addition, several other small black signatures occur along the crest that are not mapped but appear to be restricted to the centers of specific cones. This suggests that b5 volcanic activity occurred along the entire crest within the image area but lava outpourings of these recent lavas were much more restricted in the area of the trachyphonolites.

Flows depicted by a distinct orange hue correlate extremely well with the remaining mapped b5 units; however, this signature also includes several well-defined flows dated as b4. The remaining areas of this harrat display tan-brown and dark brown signatures which are generally clearly separable one from the other. They do not, however, correlate well with the b2, b3 and b4 units mapped. The combined signatures, on the other hand, sharply define the margins of this volcanic plateau.

The western lobe of the Harrat Hirmah is situated immediately to the east and extends slightly north of Ḥarrat Rahat. It has been mapped as being predominantly b3 in age, but includes a smaller contiguous b2 unit on the north. These units correlate well with tan-brown and brown signatures respectively, and are similar in hue to some of the ill-defined flows on H. Rahat. Pellaton (1980) describes H. Hirmah as deeply eroded. The eastern lobe appears on both standard and enhanced images to be largely eroded to bed rock and/or covered by alluvium.

The southern terminus of the Harrat Khaybar has suffered intense erosion, and the remaining volcanics occur as b1, b2 or b3 units capping various inselbergs/bornhardts. The b1 unit capping the buttes on the southwest correlate extremely well with a distinct light brown signature on the image. The largest outlier to the north of H. Hirmah is mapped b3 on the southeast, and the remainder of the outcrop is defined as b2. The b3 signature is similar in hue to the b3 occurring at H. Himrah, but the b2 is a distinctive tanish-brown that is not similar to any b2 mapped further south.

CONCLUSIONS

A limited number of spectral signatures displayed on contrast-enhanced and ratioed Landsat imagery correlates extremely well with the total distribution of volcanics mapped at 1:250,000 scale, a map based upon the results of extensive field surveys and regional extrapolation of lithologic units from interpretation of aerial photographs. Spectral correlation with mapped volcanic units that were defined on the basis of evolving geomorphic stages, however, met with mixed success. In some areas there is nearly perfect agreement between map and spectral units of all ages, while elsewhere agreement is much poorer.

The regional field/photo classification scheme developed for the area is based primarily upon a combination of color, weathering, khabrah development and erosion. This classification attempts to be objective but it is obvious that divisions between units are gradational through a well-defined geomorphic cycle; boundaries between can become increasingly less certain as they are interpreted on aerial photography further from the type section. Frequent confusion between upslope b2 and b3 units, in fact, was even noted in defining the basis of classification.

Spectral units within an enhanced Landsat scene are consistent and can be repeated on reprocessing. The close correlation between such spectral units and some mapped volcanic units strongly suggests that enhanced Landsat imagery can be effectively used to map volcanic flows in the arid environment of our test site. However, discrepancies with the air photo interpreted map units must be resolved in the field before the spectral classification may be accepted by the geologist. Creation of a meaningful spectral classification can contribute significantly to the accuracy of regional discrimination among volcanic flows of different ages, and at the same time greatly expedite the mapping. Conversely, spectral maps can guide extrapolation of volcanic units on aerial photography in larger scale mapping; the consistency of the spectral units should assure greater accuracy in the extrapolation of field data.

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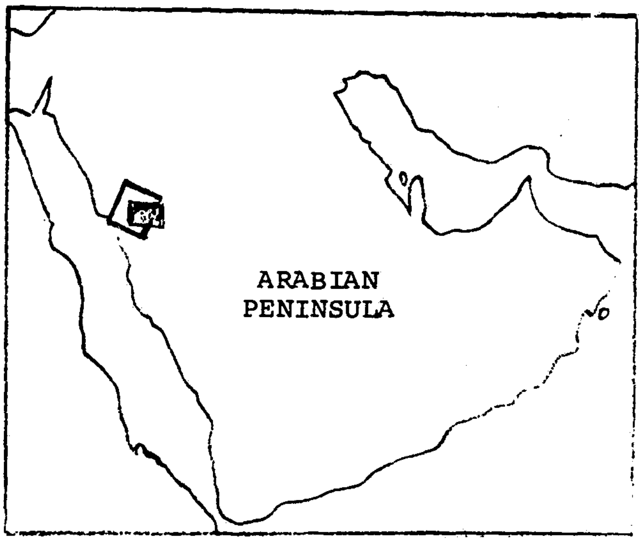


Figure 1. Index Map

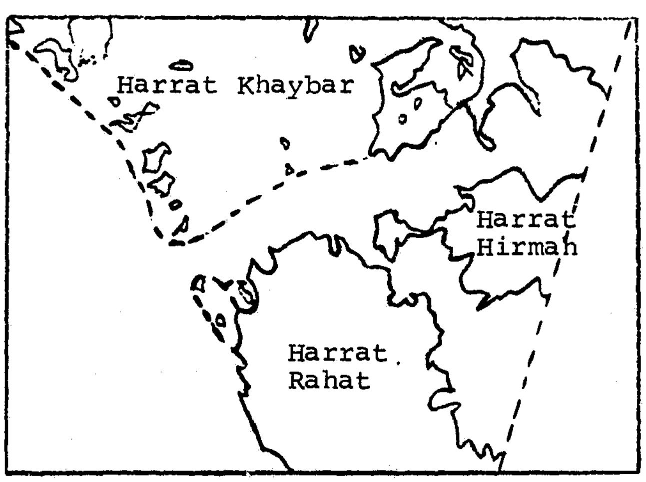
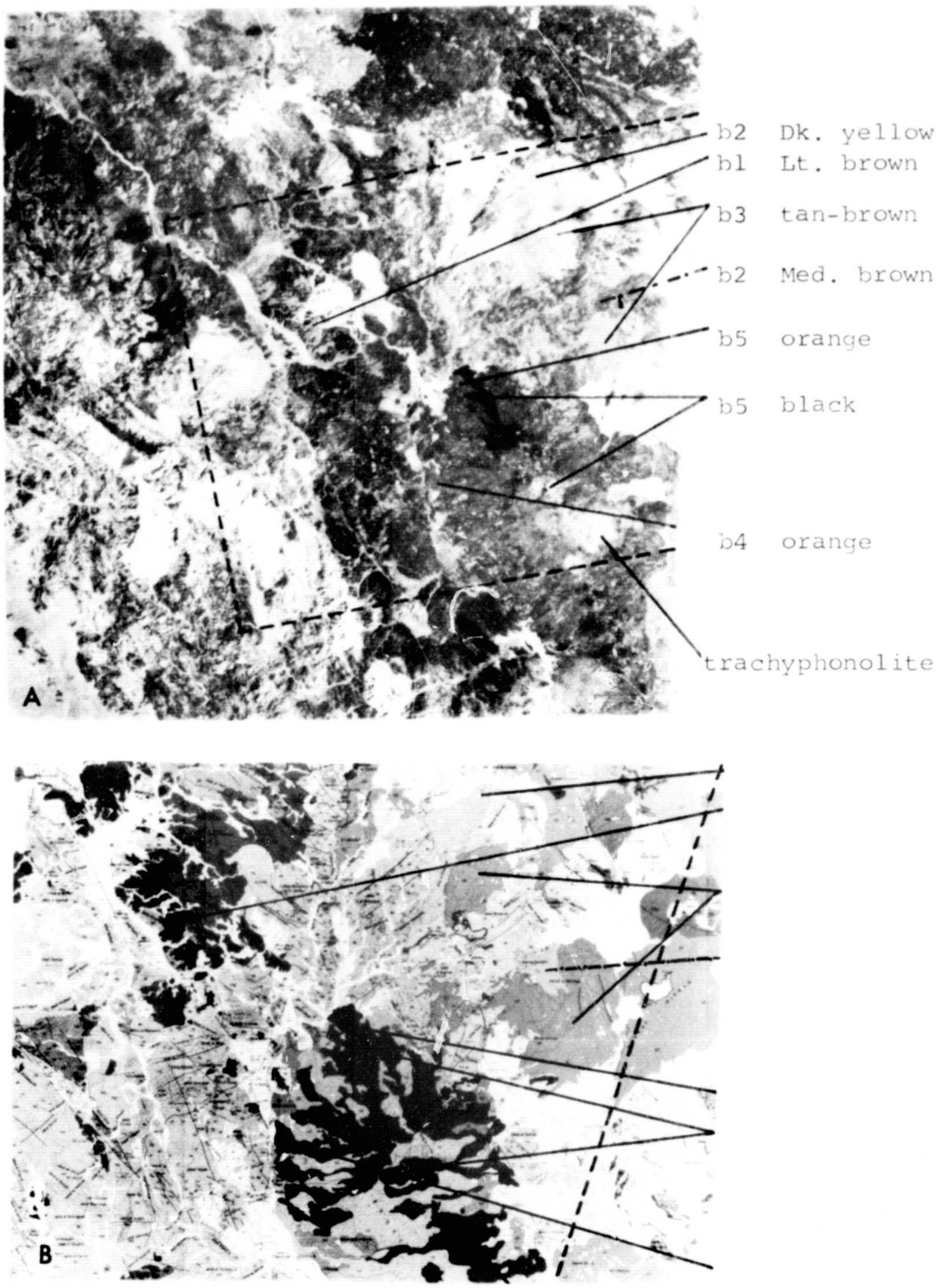


Figure 2. Margins of basalt plateaus (harrat) in image-geologic map overlap area.



---- Overlapping areas. Lines indicate same features on each format.

Figure 3. (Originals in color) A. Enhanced ratio MSS data. B. Reduced Geologic Map of the Al Madinah Quadrangle (Pellaton 1981).